NASA TECHNICAL TRANSLATION NASA TT F-15,026

CORRELATION BETWEEN THE POTENTIAL AND DENSITY FLUCTUATIONS OF A PLASMA, AND THE CONVECTIVE TRANSPORT OF PARTICLES ACROSS THE MAGNETIC FIELD IN A PENNING DISCHARGE IN THE PRESENCE OF ROTATIONAL INSTABILITY

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Translation of: "Korrelyatsiya kolebaniy potentsiala i plotnosti plazmy i konvektivnyy perenos chastits poperek magnitnogo polya v razryade penninga pri vrashchatel'noy neustoychivosti", Ukrainskiy Fizicheskiy Zhurnal, Vol. 18, No. 3, March 1973, pp. 455-460

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION
WASHINGTON, D.C. 20546 AUGUST 1973

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The study of space-time characteristics of potential and density oscillations caused by rotational instability of a plasma [1-5] is of great interest, since it can provide a comprehensive representation of the structure of a perturbation arising in a plasma and the influence of oscillations on the movement of particles across a magnetic field. This study presents the results of such research, carried out in a Penning discharge plasma with a heated cathode. /456*

The experiments were performed on equipment described in detail previously [6]. The diameter of the discharge chamber anode was 54 mm and the length was 130 mm. The bundle of primary electrons emitted by the cathode by indirect heating was limited to a diameter up to 10 mm by means of a diaphragm. In the system, stationary discharge was maintained in helium, the discharge current was $1_\alpha = 1$ A, and the voltage decrease with discharge was $V_\alpha = 100$ V. The helium pressure p and the strength of the magnetic field H, was varied between $(0.8 — 4.0) \cdot 10^{-2}$ Hg and (100 — 600) Oe to obtain the clearest picture of oscillations with a certain azimuthal mode (m = 1, 2,3) [6]. The sensor of potential and density oscillations of

* Numbers in the margin indicate pagination of original foreign text.

the plasma was a cylindrical probe with a diameter of 0.1 mm and a length of 2 mm. This was oriented along the magnetic field and could continuously move along the diameter of the anode. This same probe was used to determine the radial profiles of stationary density and stationary radial electric field [7].

As is known, it is extremely difficult to measure the oscillations of a real plasma potential, and they are usually replaced by measurements of the potential oscillations of a "floating" probe [809]. This study also used this procedure, which is valid, strictly speaking, only when the electron temperature does not change in time. Preliminary experiments on determining the instantaneous plasma characteristics in an oscillation regime with the azimuthal mode m=1, performed by means of the time selection method [9], showed that electron temperature oscillations are cophasal with potential oscillations of a floating probe. Thus, the results derived from measuring the potential oscillations of a floating probe correctly give the phase characteristics of the real plasma potential oscillations, but give oscillation amplitudes which are somewhat too low. In the case of oscillations with m=1 and m=2, within the limits of the measurement error, there are practically no electron temperature oscillations. If it is assumed that very weak electron temperature oscillations occur, then for them the same phase relationships must be expected as in the case m=1, since they have the same nature [11]. /457

In these experiments, we measured the oscillation spectra of an ion saturation current on a probe and the floating probe potential, the amplitude distribution of these oscillations over the radius of the system, and also the phase shift between oscillations of the ion current and the floating probe potential. To measure the oscillations of the saturation ion current at the

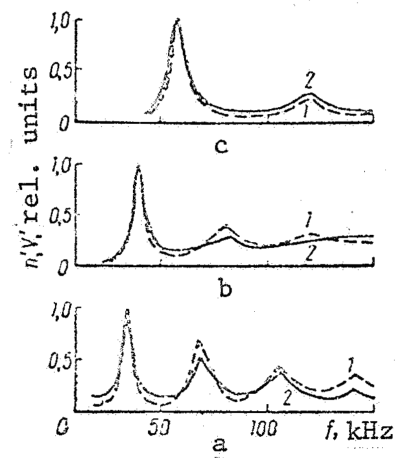

Figure 1. Spectra of oscillations of density (1) and the potential (2) of a plasma: a - m=1, p = $1.1 \cdot 10^{-2}$ mm Hg, H = 351 Oe; b - m = 2, p = $1.3 \cdot 10^{-2}$ mm, Hg, H - 168 Oe; c - m = 3, p - $1.3 \cdot 10^{-2}$ mm Hg, H = 240 Oe.

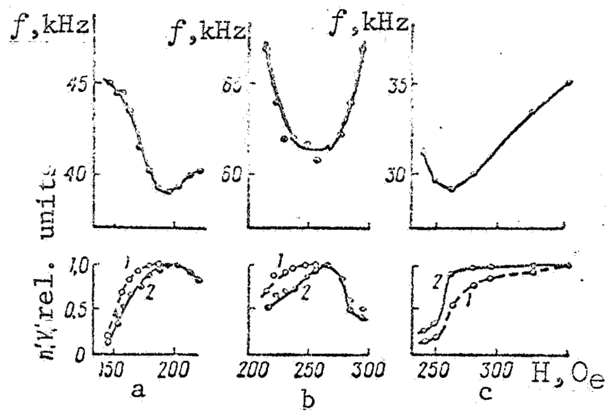

Figure 2. Dependence of f, n'(1) and V' (2) on the magnetic field. a - m = 2, p = $1.3 \cdot 10^{-2}$ mm Hg; b - m = 3, p = $1.6 \cdot 10^{-2}$ mm Hg; c - m - 1, p - $1.1 \cdot 10^{-2}$ mm Hg.

probe, the probe was grounded (i.e. connected with the cathode) by means of a small measuring resistor. An alternating signal, recorded by this resistor, was supplied to the input of a selective V6—microvoltmeter, which was used for a spectro-analysis of the signal and to determine the oscillation amplitude at the maximum of the first harmonics. The oscillations of the ion saturation current at the probe under the conditions of this experiment can be assumed with sufficient accuracy to be proportional to the plasma density oscillations [6]. To measure the potential oscillations of a floating probe, the probe was grounded by means of a capacity divider with a rather high impedance (1-5 Megohm) in the range of frequencies being studied. The signal from the divider was also supplied to the input of the selective V6—microvoltmeter for a spectral analysis of the signal and to determine the oscillation amplitudes.

The phase shift between the plasma density oscillations and the floating probe potential oscillations was measured as follows. A fixed reference probe which had a cathode potential was introduced into the plasma. The oscillations of the ion saturation current in the circuit of this probe, which were intensified by the selective V6 microvoltmeter at a frequency of the first harmonics, served as the reference signal and were supplied to the corresponding input of an F2-1 phase meter. A signal from the measuring probe, which was amplified in this way, was supplied to the other input of the phase meter. The probe was connected by turns to the ohmic and capacitive loads. The phase shift between the density oscillations and the potential oscillations was determined by subtracting the results of the /458
two measurements, and additional control of the phase shift was accomplished by oscillography of the amplified signals. The use of a certain probe for measuring oscillations both of density and of potential, and the use of a reference probe

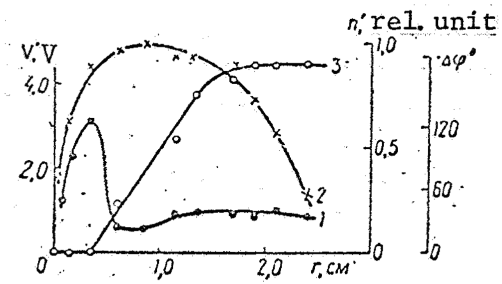

Figure 3. Radial profiles V' (1), n' (2) and Δφ (3), m = 1, p = 1.1· 10^{-2} mm Hg, H-276 Oe.

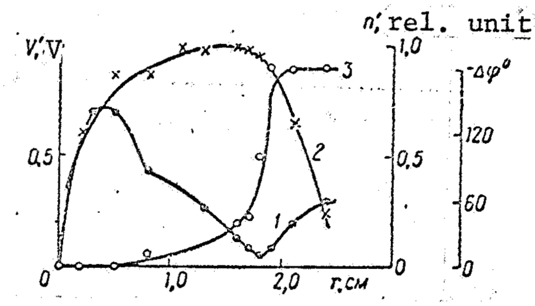

Figure 4. Radial profiles V' (1), n' (2) and Δφ (3), m=2, p= 1.3·10^{-2} mm Hg, H-177 Oe

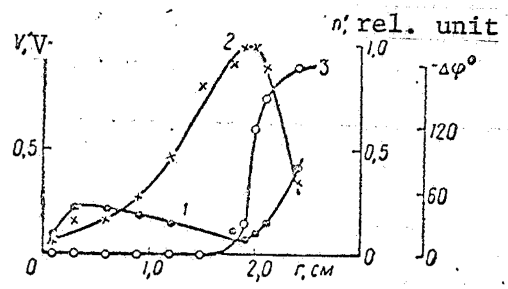

Figure 5. Radial profiles V' (1), n' (2) and Δφ (3), m=3, p = 1.6·10^{-2} mm Hg, H=220 Oe.

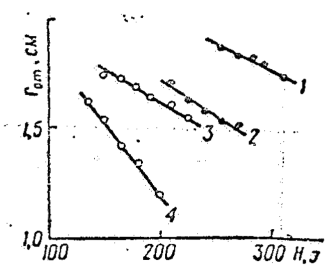

Figure 6. Dependence of r_{om} on magnetic field: 1 - m = 3, p = 3.4·10^{-2} mm Hg; 2 - m = 3, p = 1.3·10^{-2} mm Hg; 3 - m = 2, p = 1.3·10^{-2} mm Hg; 4 - m = 2, p = 0.8·10^{-2} mm Hg.

reduced to a minimum possible errors in measuring the phase shift related to the azimuthal clearance when the probe moved along the radius of the system. The error in measuring the phase shift in these experiments did not exceed ±6°.

A study of the spectra of the oscillations of the plasma potential and density showed that for all three modes they were practical identical. The data given in Figure 1 may illustrate this (the amplitudes of the oscillations are normalized to the maximum of the first harmonics). The dependencies of the amplitude of the potential and density oscillations on the strength of the magnetic field also qualitatively coincide, and for the modes m = 2 and 3, they have the form of curves with maxima (Figure 2, a and b). In the case of m = 1 mode, the amplitude of the potential oscillations sharply decreases at first with an increase in the magnetic field, and then remains practically unchanged up to the transition to the turbulent regime (Figure 2, c). As it was already observed previously [6], there is a sharp correlation between the dependencies of amplitude and frequency of oscillations on the magnetic field: a minimum of the oscillation frequency corresponds to the maximum of the oscillation amplitude (or to a maximum value in the case m = 1). In the region of mode coexistence [6], the frequency of the disappearing mode increases and the frequency of the developing mode decreases at the same time. These features of the amplitude-frequency characteristics of oscillations cannot be explained within the framework of linear theory of rotational instability [1-5], and they are apparently due to non-linear phenomena. Actually, as was shown in the non-linear theory of rotational instability which was recently advanced [12], there is a shift of frequency towards smaller values with an increase of the oscillation amplitude. A similar result of non-linear theory of collisionless drift waves was obtained in [13].

The potential oscillation amplitude in the case m = 1 is usually several volts, and in the case m - 2 and 3, it is several tens of volts. Measurements of the phase shift of oscillations of density and potential along the radius of the system with respect to oscillations in the reference probe showed that the potential oscillation phase changes greatly over the radius of the system, whereas the phase of the density oscillations remains almost unchanged, with the exception of a narrow near-axial layer. Figures 3-5 present the radial dependencies (which are typical for the azimuthal modes m = 1, 2,3) of the density oscillation amplitudes n', the potential oscillation amplitude V', and the phase shift $\Delta\varphi$ between these oscillations. Attention should be called to the following characteristics of these distributions. /459

There is a sharp minimum of the radial dependence of the floating potential oscillation amplitude in the region of the maximum of the density oscillation amplitude. As has been found earlier [11], the radial coordinate of the amplitude maximum of the density oscillations r_{0m} is determined by the condition that the wave phase velocity and the velocity of the azimuthal ion drift be equal. With an increase in the strength of the magnetic field and a decrease in the gas pressume in the discharge, the aplitude minimum of the potential oscillations (i.e. r_{0m}) is slightly shifted toward the system axis as is shown in Figure 6. A similar effect was observed in the case of rotational instability in direct discharge with a cathode [5].

The phase of the potential oscillations changes along the radius by approximately 180°. This change is primarily localized close to r_{0m}. Usually, the phase of the potential oscillations lags behind the density oscillations. This lag in the near-anode layer of the plasma $(r_{0m}<r<r_a)$ is close to 180°,

in the near-axial plasma $(0<r<r_{0m})$ it is close to zero, and when $r=r_{0m}$ it is close to 90° as would be expected for the case of rotational instability.

The experimental data enumerated above and shown in Figures 3-5 make it possible to describe the perturbation of the density and the potential of a plasma in the form $\tilde{V}=V'(r)\cos[\omega t-m\Theta-\Delta\varphi(r)]$, and to determine the magnitude and direction of the variable electric fields $\tilde{E}_r$ and $\tilde{E}_\Theta$ arising in a plasma. Computations show that, in agreement with conclusions of the linear theory of rotational instability [3], in the case of all three modes, the variable radial electric field on the axis of the density "tongue" proceeds in a direction opposite to the stationary electric field and the variable azimuthal electric field — in the direction of the wave motion. The value of $\tilde{E}_r$ on the axis of the density "tongue" in the case of the m = 1 mode reaches 2-3 V/cm and in the case of the mode m = 2 and m = 3 it reaches 0.5-0.7 V/cm. The variable azimuthal electric field on the axis of the density "tongue" for all three modes strives to zero as the anode is approached, and reaches a maximum value on the order of 1 V/cm when m = 1 and 0.1 V/cm and m = 2 and 3 in the vicinity of r_{0m}. /460

The existence in the density "tongue" of an azimuthal electric field in the direction of its motion means that the particle drift under the action of the crossed fields $\tilde{E}_\Theta$ and H leads on the average to the formation of a convective radial flow of particles in the direction of the anode. The magnitude of this flux per unit length of the plasma column at a distance of r from the system axis is

$$\Gamma_k=\frac{2\pi r}{T}\int_0^T\tilde{n}\cdot\frac{\tilde{E}_\Theta}{H}\,dt=\frac{\pi mn'V'}{H}\cdot\sin\Delta\varphi, \qquad (1)$$

where T — is the oscillation period.

It is of interest to establish the value of Γ_k and to compare it with the values of the radial electron fluxes caused by the stationary density gradient

$$\Gamma_n = -2\pi r D_{e\perp} \cdot \nabla n \qquad (2)$$

and the stationary radial electric field

$$\Gamma_E = 2\pi r \mu_{e\perp} E_r n. \qquad (3)$$

Here n is the stationary plasma density, E_r is the stationary radial electric field, and $D_{e\perp}$ and $\mu_{e\perp}$ are the classical coefficients of diffusion and mobility of the electrons across the magnetic field. This type of determination was made for all three modes in the region of the plasma where there was a maximum of the density oscillation amplitude. The magnitudes of the fluxes and the total flux $\Gamma_\Sigma = \Gamma_n + \Gamma_E + \Gamma_k$, referred to the plasma density on the axis of the system n_0, are shown in the table. This table also gives, for purposes of comparison, the value of $D_{e\perp}$, the Bomov diffusion coefficient D_B and the effective diffusion coefficient $D_{eff} = D_{e\perp} + \frac{\Gamma_k}{2\pi r \cdot \nabla n}$.

It may be seen that all three modes of oscillations make a great contribution to the total flux of particles across the magnetic field. The size of this contribution increases when the modes are readjusted with an increase in the magnetic field, and for the data given in the table it comprises 80, 25, 40% for the m=1, 2, 3 modes. When m = 2 and 3, the convective flux caused by instability is comparable to the fluxes caused by the /461
stationary density gradient and the radial electric field, and when m = 1 it is almost ten times greater than these fluxes. This

$p \cdot 10^2$, mm Hg	H, Oe	m, cm	r, cm	$\frac{1}{n_0} G_k \cdot 10^{-4}$, cm^3/sec	$\frac{1}{n_0} G_n \cdot 10^{-4}$, cm^3/sec	$\frac{1}{n_0} G_E \cdot 10^{-4}$, cm^3/sec	$\frac{1}{n_0} G_\Sigma \cdot 10^{-4}$, cm^3/sec	$D_{e\perp} \cdot 10^{-4}$, cm^2/sec	$D_B \cdot 10^{-5}$, cm^2/sec	$D_{eff} \cdot 10^{-4}$, cm^2/sec *
1,3	177	2	1,6	1,4	2,8	1,6	5,8	1,2	1,2	1,9
1,6	220	3	2,0	2,7	2,8	1,1	6,6	1,0	1,2	1,8
1,1	270	1	1,1	20	2,6	2,1	25	0,85	1,8	6,9

*Commas represent decimal points.

result qualitatively agrees with the estimate of the influence of different oscillation modes on the movement of particles across the magnetic field when there is a change in the radial density profile [14]. If the fact is taken into account that for the discharge regimes given in the table, the charged particle concentration on the axis of the system is $(5-7) \cdot 10^{12} cm^{-3}$ then — within the limits of accuracy of these estimates — the total flux of electrons across the magnetic field $\Gamma_\Sigma \cdot L$ (L is the anode length) is close to the discharge current $I_\alpha = 1$ A. This indicates that under the conditions of these experiments other mechanisms do not make a great contribution to the transport of particles across the magnetic field. The effective diffusion coefficient for m = 2 and 3 modes exceeds the classical coefficient by more than a factor of two and it is more than 8 times greater for the m = 1 mode. In every case, the effective diffusion coefficient is less than the Bomov coefficient. The values of D_{eff} given in the table for different oscillation modes are close to the calculated values on the basis of the radial plasma density profile [14].

Thus, this article has described the characteristics of the potential perturbation and the Penning discharge plasma density for different modes of oscillations caused by rotational instability. It was established that the perturbation structure causes the convective flux of particles across the magnetic field. An estimate was made of this flux, and it was found that for all three oscillation modes it comprises a significant portion of the total flux, and determines the increased motion of particles across the magnetic field observed with the occurrence of rotational instability. An analysis of the data described previously [6, 8, 9, 11, 14] and the data obtained in this study leads to the conclusion that the occurrence of rotational instability in a Penning discharge plasma with a heated cathode is a necessary condition for discharge combustion in the case of high magnetic fields and low gas pressures, when the classical transport mechanisms do not provide the necessary flux of particles across the magnetic field.

In conclusion, the authors would like to thank A. S. Popovich for valuable discussion.

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Translated for National Aeronautics and Space Administration under contract No. NASw 2483, by SCITRAN, P. O. Box 5456, Santa Barbara, California, 93108.

STANDARD TITLE PAGE

1. Report No. NASA TT - 15,026	2. Government Accession No.	3. Recipient's Catalog No.
4. Title and Subtitle CORRELATION BETWEEN THE POTENTIAL AND DENSITY FLUCTUATIONS OF A PLASMA, AND THE CONVECTIVE TRANSPORT OF PARTICLES ACROSS THE MAGNETIC FIELD IN A PENNING DISCHARGE IN THE PRESENCE OF ROTATIONAL INSTABILITY		5. Report Date August 1973
		6. Performing Organization Code
7. Author(s) L. I. Romanyuk and V. M. Slobodyan		8. Performing Organization Report No.
		10. Work Unit No.
9. Performing Organization Name and Address SCITRAN Box 5456 Santa Barbara, CA 93108		11. Contract or Grant No. NASw-2483
		13. Type of Report and Period Covered Translation
12. Sponsoring Agency Name and Address National Aeronautics and Space Administration Washington, D.C. 20546		14. Sponsoring Agency Code

15. Supplementary Notes Translation of: "Korrelyatsiya kolebaniy potentsiala i plotnosti plazmy i konvektivnyy perenos chastits poperek magnitnogo polya v razryade penninga pri vrashchatel'noy neustoychivosti", Ukrainskiy Fizicheskiy Zhurnal, Vol. 18, No. 3, March 1973, pp. 455-460.

16. Abstract

Correlation of the amplitude, frequency and phase characteristics of the density and potential oscillations resulting from the rotational instability of a hot cathode Penning discharge plasma was studied. An attempt was made to explain qualitatively the oscillation amplitude-frequency characteristics by non-linear effects. The data are obtained on the plasma density and potential perturbation for the oscillations with azimuthal mode m = 1, 2, 3. The structure of the perturbation is established to give rise to a convective flow of particles across the magnetic field. The magnitude of the convective flow is estimated. This flow is shown to form a significant part of the total flow and to determine in essence an increase in the particle escape across the magnetic field observed under development of rotational instability.

17. Key Words (Selected by Author(s))	18. Distribution Statement Unclassified - Unlimited

19. Security Classif. (of this report)	20. Security Classif. (of this page)	21. No. of Pages	22. Price
Unclassified	Unclassified	13	